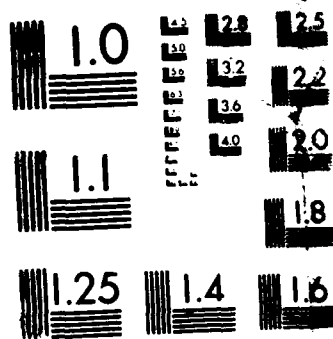


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<p>A nonlinear theory of turbulent coherent structures near walls has been developed based on the assumption that the eddies are flat, with large horizontal dimensions compared to their thickness. Turbulence in the outer part of the boundary-layer may be modelled as a linearly driven system with nonlinearities confined to the near wall region. a new model for near wall turbulence based on the concept of an instantaneous mixing length gives a mean velocity profile (valid from the wall to the beginning of the log region. The effect of Large Eddy Break-up devices on the boundary layer was modelled as a wake deficit. The wake acts as a barrier to structures crossing the wake. Measurements of the skin friction behind LEBU's using a variant of the Stanton tube are in agreement with other techniques. Active wall experiments confirmed the theoretical predictions from the flat eddy model that growth of 3-D</p>			
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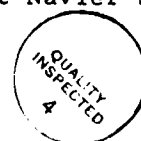
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Objectives

The overall objectives of the research effort were to understand and model the structure of turbulent boundary layers, in particular the turbulence sustaining mechanisms, and apply the results to the control of transitional and turbulent boundary layers. Particular control devices investigated were Large Eddy Break-Up devices and active walls.

Status of the research effortTheoretical Work1. Boundary Layer Turbulence Structure

i) Flat-eddy model of the fluctuating field. Turbulent mixing and momentum transport in the near-wall region of a boundary layer are dominated by eddies of large horizontal scales but which are thin, i.e., have a boundary layer structure by themselves. For such "flat" eddies the inviscid dynamics of their evolution simplifies considerably in that the effects of horizontal pressure gradients are generally small and may be neglected (Russell and Landahl, 1984), a finding in support of the basic assumption in Prandtl's mixing-length theory (Landahl, 1984). The flat-eddy model allows the calculation of the nonlinear evolution of the eddy in a fairly simple manner. It was discovered that a singular behavior is possible after a finite time producing a flow field strongly resembling that seen in the experiments by Kim et al. (1971) visualizing turbulent bursting (Henningson, 1985, Landahl & Henningson, 1985). The effects of viscosity manifest themselves after a time of the order $\ell^{2/3} \nu^{-1/3} (U')^{-2/3}$ primarily through a lengthening of the convected eddy and a weakening of the strength of the internal shear layer formed (Landahl, 1983). A comparison of the results from the simplified model with results from a direct Navier-Stokes numerical



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simulation (Breuer & Landahl, work in progress) shows that the nonlinear development of an isolated eddy is very well described by the model.

ii) Boundary layer turbulence modelled as a driven linear system. Recent experiments using conditional sampling indicate that many processes in boundary layer turbulence are approximately linear in the sense that they are governed primarily by linear interactions between the fluctuations and the mean shear flow. For example, Variable Integration Time Averaging (VITA) sampled velocity signatures scale with the threshold parameter in a manner consistent with linearity (Landahl, 1987). Also, recent measurements of simultaneous wall pressure fluctuations and VITA-educed fluctuation velocity signatures show that the pressure is linearly related to the velocity fluctuations. It was demonstrated that their effects are the largest for fluctuations of small spatial scales. Thus, the eddies of large horizontal scales, which are the ones giving the highest contributions to the average Reynolds stress, may be treated with a linear model. The nonlinearities appear to manifest themselves primarily in the near wall region.

On the assumption that the nonlinear driving of the stress producing fluctuations are important only in a thin region near the wall (of a thickness possibly as small as 50 wall units) an active-wall model for the turbulent field has been formulated (Landahl, 1986). Approximating the mean flow as parallel, one finds that the region outside the active layer is governed by the Orr-Sommerfeld equation. Preliminary findings from this formulation are that the classical mixing-length theories of Prandtl and by Taylor may be shown to result from approximations from the inviscid version of the new theory and that the mean velocity profile is found to be logarithmic in the constant-stress region (work in progress).

ii) New turbulence model for the near wall region. A new model for near-wall turbulence in a boundary layer has been constructed (Haritonidis, 1987) based on the concept of an instantaneous mixing length (Landahl, 1984) and the time scales of the bursting process. The model is valid from the wall to the beginning of the logarithmic region and no separate assumption need be made regarding the vertical velocity fluctuations. Instead they are modelled directly as the time rate of change of the vertical displacement of a fluid element. The mean velocity distributions obtained from this model for plane, channel and pipe boundary layers is found to agree well with measured data for the region between the wall and the beginning of the logarithmic region.

2. Boundary Layer Control

i) The effects of drag reduction measures on the structure of turbulence.

Based on the inviscid theory for eddies of large horizontal dimensions (Russell & Landahl, 1984) a qualitative analysis of the effects of various drag reduction measures was carried out. The different phases of bursting may be modelled in a qualitative manner from this theory. Two different active bursting mechanisms may be distinguished: a) instability of the internal shear layer formed through stretching of spanwise vorticity near the wall and b) spanwise convergence of fluid elements forcing, through continuity, rapid ejection of the fluid. It was concluded that in order to effect the drag it is necessary to interfere with the spanwise motion of small scale eddies near the wall. Drag reducing polymers do this inhibiting vortex stretching. Streamwise wall riblets (Walsh, 1982) can do this provided their spacing is less than the dimensions of the low-speed streaks.

Large-Eddy Breakup devices (LEBUs), on the other hand, appear not to be able

to produce an effect on the small scales in the near-wall region.

ii) Large Eddy Breakup Devices. The effects of LEBUs on the structure of boundary layer turbulence was studied with the aid of two different models (Balakumar, 1986, Balakumar & Widnall, 1986). In the first, potential flow wing theory was employed to calculate the damping effect on an incoming sinusoidal eddy by the LEBU, modelled as a flat plate with zero thickness. Both two-dimensional and three-dimensional wing theory was used. It was found that the LEBU reduces the amplitude of the gust substantially to as much as one fifth of its original strength or even less. A second flat plate in tandem can produce an additional reduction factor of the same order.

The second model dealt with the effect of the wake behind the LEBU on the surrounding fluctuating flow field. The wake was modelled as a thin layer of low velocity in the boundary layer profile. The interaction between this layer and an incoming vortex pair (or a vortex ring in the three dimensional case) was determined using vortex dynamics. Both linear theory and direct numerical calculations were employed, the latter making use of the cloud-in-cell technique. It was found that, if the incoming eddy is only moderately strong, the presence of the velocity defect (wake) causes the incoming eddy to rebound from it. Hence, the wake may act as a barrier to turbulent eddies travelling towards or away from the wall supporting the suggestion by Mumford & Savill (1984). This may explain the increase in turbulence intensity above the wake that has been observed by several investigators (Bertelrud et al. 1982, Guezennec & Nagib, 1985). The calculations also demonstrate how a vortex impinging on the wake excites instability waves in the wake.

iii) Active flexible wall. In this work the possibility of affecting a preexisting near-wall eddy by moving a portion of a flexible wall in a prescribed way so as to make it less susceptible to breakdown and thereby reduce the turbulence production was investigated. To this purpose, the flat-eddy model of Landahl (1984) was employed. The calculations based on this model showed that it would be possible to counteract the formation of an internal shear layer by moving the wall in a travelling-wave fashion with appropriate phasing. The wall amplitude needed was found to be quite small. The theoretical analysis was employed to guide the design of an experiment to test the concept (Breuer et al. 1986) that was found to give a qualitative confirmation of the soundness and effectiveness of the method (see below).

Experimental Work

1) Wind Tunnel Facility

The Low Turbulence Wind Tunnel (LTWT) was fitted with a flat plate and computer controlled traverse for boundary layer measurements. In addition, a complete data acquisition facility and hot wire equipment were acquired and made operational.

2) Instrumentation

i) Mean wall shear stress measurement. A movable Stanton tube (Fulcher, 1986) was constructed and successfully tested for the rapid spatial measurement of wall shear stress. Such a capability was necessary for the drag reduction work involving LEBUs.

A very small channel was machined on the contact surface between the wall

and a small, wedge shaped (as viewed from the side) probe. The channel opening acts as a Stanton tube and was designed to be imbedded in the viscous sublayer of the flows of interest. The probe is mounted on a sting so that it can be easily placed at any downstream or spanwise location with respect to the LEBUs.

ii) Fluctuating shear stress. Work involving the measurement of the fluctuating shear stress revealed that the measurements to date have been in serious error due to either improper calibration and/or excessive heat transfer problems to the substrate when hot-film probes were used. A systematic study of the problems with hot-films showed the limitations of their use and the advantage of using hot-wires mounted flush with the wall (Alfredsson, P.H. & Haritonidis, J.H. 1985, Alfredsson, Johansson, Haritonidis & Eckelmann, 1986). It was shown that the correct ratio of $\tau_{rms}/\bar{\tau}$ is about .4 rather than .26, as had been previously verified, and that the viscous sublayer is, in fact, the most turbulent part of the boundary layer in terms of the ratio of the velocity fluctuations to the mean velocity.

3) Boundary Layer Control

i) Large Eddy Break-Up (LEBU) devices. Experiments with tandem LEBUs (Mangus, 1985) focused on the overall development of manipulated and non-manipulated boundary layers and in particular on the bursting frequency. The major results were that a) the skin friction drops downstream of the device and then returns monotonically to its undisturbed value after about 150-200 boundary layer thicknesses, in agreement with the results compiled by Westphal (1985), b) the bursting frequency reflects in a roughly

proportional manner the changes in skin friction, and c) the return of the skin friction to its undisturbed value coincides with the disappearance of the wake of the LEBUs, in accordance with the flow visualization findings of Mumford & Savill (1984). The overall net drag reduction was approximately 4% for the experimental arrangement used in this investigation.

- ii) Active flexible wall. As the first step towards building "smart" walls for the control of transitional and fully turbulent flows, a small portion of the wall (flat plate in the LTWT) was converted into an active wall. Eight transverse slots on the plate surface were covered by a thin latex sheet, forming eight cells in which the pressure can either be increased or decreased relative to the surrounding pressure, thus deforming the latex. The result is a bump or depression. By successively overpressurizing or underpressurizing the cells, a travelling 'wave' is obtained at the desired speed. Results on the control of isolated disturbances in a laminar boundary were reported by Breuer et al. (1986). It was demonstrated that the growth of laminar-like, localized disturbances could be delayed by the application of a counter disturbance as described above.

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DEGREES AWARDED

- 1) Mangus, J.F., M.S. 1984. Thesis title: "Preliminary Measurements of Drag and Bursting Frequency in a Manipulated Turbulent Boundary Layer."
- 2) Fulcher, K.L., M.S. 1986. Thesis title: "A Probe for Measuring Skin Friction in Disturbed Turbulent Boundary Layers."
- 3) Balakumar, P., Ph.D. 1986. Thesis title: "Effects of Large-Eddy Breakup Devices in a Turbulent Flow."

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